NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
INVENTIONS AND CONTRIBUTIONS BOARD
SPACE ACT AWARD APPLICATION

BACKGROUND:

THE NASA SPACE ACT MONETARY AWARDS PROGRAM FOR SIGNIFICANT SCIENTIFIC AND TECHNICAL CONTRIBUTIONS

The objectives of this program are to provide official recognition of, and to grant equitable monetary awards for those inventions and other scientific and technical contributions that have helped to achieve NASA's aeronautical, commercialization, and space goals; and to stimulate and encourage the creation and reporting of similar contributions in the future. To accomplish these objectives, the Inventions and Contributions Board is authorized to recommend the granting of monetary awards in amounts up to $100,000 in accordance with the provisions of the National Aeronautics and Space Act of 1958, and to grant monetary awards in amounts up to $10,000 in accordance with the provisions of the Government Employees Incentive Awards Act of 1954. Space Act awards can be made to any person with no restriction as to employer, and in accordance with the regulations as specified in the Federal Register Vol. 55, No. 5, (14 CFR Part 1240). Awards made under the authority of the Incentive Awards Act can be made to U.S. Government employees only.

GUIDELINES:

In determining the merits of an invention or a contribution, the Board depends primarily on the information provided by the contributor(s)/technical evaluator in the Space Act Award Application. Furthermore, the Board recognizes that NASA technical personnel are the best sources of reliable information concerning contributions made by employees of NASA or by employees of NASA's contractors whose activities are under their cognizance. For this contribution, it is appropriate for the contributor(s)/ technical evaluator to supply the information that the Board requires in order to make a recommendation that is equitable to both the contributor(s) and NASA. We are therefore asking you to assist the Board by completing, accurately and thoroughly, the application which follows these explanatory remarks. For your convenience we suggest that you familiarize yourself with the contents of the application by reading it completely before answering the questions. Please provide all pertinent facts, specific details, explanations, and opinions regarding seven important factors that characterize the contribution. These factors are: (1) Description, (2) Significance, (3) Stage of Development, (4) Use, (5) Creativity, (6) Recognition and (7) Tangible Value. The Board welcomes any additional information that you believe will contribute to the completeness of its deliberations. If you find it necessary to modify or expand the format of the application in order to provide such extra information, please do so.

REQUIRED DOCUMENTATION AND AWARDS LIAISON OFFICE RESPONSIBILITY:

Please be thorough and candid with your evaluation. Each section must be filled in, and where appropriate, signed by the evaluators. **In no case should the evaluator be identified as a contributor**. The full legal name, employer's name and percentage contribution for each contributor is mandatory and at least one NASA official must sign in Section II to attest to NASA's sponsorship, adoption, support or use of the contribution. If any supplementary materials are provided; e.g., additional sheets, technical papers, engineering drawings, videotape, audio cassettes, photographs, computer diskettes, etc., each must be marked and identified by the NASA Case Number and be converted to electronic format. The names and contact information for individuals familiar with the contribution would be helpful for evaluation. The Awards Liaison Officer of the NASA Center where the contribution is supported is responsible for accepting the application and subsequent submission to the Board. Please ensure that the contributors have signed a Privacy Act statement such as that forwarded to the Awards Offices by the ICB on May 13, 1992. All contributions should be officially reported to NASA by submission of Form 1679 Disclosure of Invention and New Technology (Including Software). In no case may a software innovation be reported on this form unless the software has been officially released by NASA to qualified users and reported to the ICB.

The Board sincerely appreciates the time and effort you will devote to the completion of the Space Act Award Application. We pledge to take prompt action to review and process your application. It is our intent to expeditiously reward excellence.

NASA FORM 1329	Inventions and Contributions Board *Space Act Award Application*	NASA Case Number:	Date:
SECTION I ***SPACE ACT AWARD APPLICATION***			
TITLE MAPGEN: Mixed-Initiative Activity Plan Generation – A tool for generating complex activity plans for spacecraft missions, including Mars Exploration Rover mission			

1. DESCRIPTION.

a. Briefly describe the contribution. In addition, if peer-reviewed publications by contributors have been accepted on this topic in refereed journals or for refereed conference papers, please attach a copy with this form as a supplement.

MAPGEN (Mixed-initiative Activity Plan GENerator), is an advanced multi-mission system for building and editing activity plans for spacecraft. It uses state of the art artificial intelligence techniques to assist the user in the generation of complex, robust, and safe plans. MAPGEN extends an existing mission planning system, called APGEN, by adding advanced planning and constraint reasoning techniques, resulting in a plan generation tool that offers revolutionary capabilities to its users. MAPGEN is currently being used twice daily, as a mission critical system in the uplink process to do the high-level planning for both rovers of the Mars Explorations Rovers (MER) mission on the surface of the Red Planet. When MAPGEN was used for the first time to command the Spirit rover on the 16th Martian day (or Sol) on January 18th, it became the first Artificial Intelligence based system to be used in operating a space platform on the surface of another planet.

In this context, an *activity plan* is a high-level description of activities that a spacecraft performs to fulfill its mission goals for some specific period of time. The plan may include engineering activities that are needed to maintain the health and safety of the spacecraft, as well as activities to generate data products for science. Such activity plans form the basis of sequences that are executed onboard the spacecraft. Formulating activity plans requires juggling complex spacecraft constraints to ensure that flight and mission rules are enforced while also working to achieve a high-quality science return. At one time, activity plan generation was done almost completely manually. But, as the complexity of missions and spacecraft has increased over time, the number of constraints and interactions that human planners have had to deal with has increased proportionately. This has led to the development of automated tools for assisting with the enforcement of flight/mission rules. However, prior to MAPGEN, the automation has been limited to flagging violations (for example, over-subscription of the data buffers onboard), leaving the human planner to determine how to fix violations while having to take into account the many intricate rules and interactions involved.

On MER, the tactical commanding process has been designed to command the two rovers every day, requiring that new activity plans be generated each day within a very narrow time window. This, combined with the complexity of the MER rovers and the demand for high science return, places a great burden on the Tactical Activity Planners or TAPs, who are responsible for generating these daily activity plans. In order to enable these human planners to effectively perform their job under these circumstances, and to optimize the quantity and quality of science, the MER project chose MAPGEN as a mission-critical part of the mission operations software system.

There are a number of significant capabilities that MAPGEN brings to the table. Among these are:

- Automated plan generation allows the TAP to generate a rough sketch plan with all the day's science and engineering constraints, within minutes.
- User-guided, incremental plan construction, with varying degrees of automation, allows the TAP to bring his/her experience to bear by influencing the quality of the resulting plan.
- Active flight rule and constraint enforcement allows the TAP to confidently build and edit robust plans, passing on the routine and arduous task of enforcing flight and mission rules to the system.
- Plan visualization and editing capabilities allow the TAP to visually inspect and verify plans in order to ensure that the plan fulfills the science and engineering intent.
- Resource modeling capabilities ensures that the plans generated by MAPGEN are consistent with the availability of critical resources onboard the rovers, particularly those related to energy and data.

The system can be easily adapted to multiple missions because activity types, flight rules, and other mission-specific information are specified in tool adaptation files in a declarative manner and are not bundled into the search engine used for generative planning. This model-based approach ensures that when adapting the system to future missions, the core reasoning engine can be used without changes, thus reducing development and verification effort and cost. Specifically, the development effort is limited to the mission-specific aspects encoded in the adaptation and the verification effort can be focused almost exclusively on that adaptation.

. *In addition, if peer-reviewed publications by contributors have been accepted on this topic in refereed journals or for refereed conference papers, please attach a copy with this form as a supplement.*

The following support items are attached to provide a more complete of description of MAPGEN:

- MAPGEN: MAPGEN: Mixed Initiative Planning and Scheduling for the Mars '03 MER Mission, Intnl. Symposium on AI and Robotics in Space, Nara Japan, 2003.
- MAPGEN: Mixed-Initiative Planning and Scheduling for the Mars Exploration Rover Mission, IEEE Intelligent Systems, Jan 2004.
- MAPGEN: A Mixed Initiative System for the MER Mission, International. Conf. on Automated Planning & Scheduling, Demo track, ICAPS2003, Trento, Italy.
- Constraint Maintenance with Preferences and Underlying Flexible Solution, Constraint Programming Conference, Cork, Ireland, 2003.
- APGEN: A multi-mission semi-automated planning tool., Proceedings of the 1st International Workshop on Planning and Scheduling for Space, Oxnard, California, 1997.
- Planning in interplanetary space: Theory and practice. In Artificial Intelligence Planning Systems, 2000.

b. In what NASA program, project or mission has this contribution been used or will be utilized and to what extent? (*include any non-aerospace commercialization applications)*

The MAPGEN software is an integral part of the Ground Data Systems (GDS) for the ongoing Mars Exploration Rover (MER) mission. It plays a critical role in the tactical uplink process as the main tool for generating valid activity plans for each upcoming sol (Martian day). The MER mission has opted for every-Sol commanding. This means that each Sol (Martian day), telemetry from the MER rovers is analyzed to determine their state of health and the nature of their surroundings. The scientists then meet as the Science Operations Working Group (SOWG) and discuss which specific observations should be targeted for the current Sol, based on the current situation and the long-term strategic plan. Since resource and other limitations are only known to a rough approximation at this stage, the scientists are encouraged to form a prioritized list of observations that oversubscribes the resources.

Each observation consists of a coordinated set of activities. The coordination involves constraints that are determined from a statement of the scientific intent that is attached to the observation. One of the concerns in previous missions has been that, during the pressures of detailed planning, observations might get moved or modified in a way that defeats their scientific purpose. This is known as *intent tracking*. Adding constraints that are based on the intent helps ensure that the observations fulfill their scientific purpose. For example, constraints may be entered that require an instrument calibration to be near the operational use of the instrument, or require an imaging activity to be late in the Sol when shadows are longer. In consultation with the SOWG Chair and other experts, the Tactical Activity Planner (TAP) uses the Constraint Editor portion of the MAPGEN software to enter temporal constraints that capture the intent in a machine readable form. As constraints are added, an underlying constraint-propagation engine monitors the input for inconsistencies. If any are found, the tool immediately warns the user and pinpoints the constraints involved.

The coordinated observations, together with engineering requests, communication opportunities, and the current state of the rover, form the input for the main MAPGEN tool. The TAP operates MAPGEN and uses it to prepare a detailed activity plan and schedule that fits within the resources, as determined by the higher-fidelity modeling process available to MAPGEN. This typically requires a process of modification and compromise using interactive features of the system, carried out under the watchful eyes of both the SOWG chair and the Tactical Uplink Lead (TUL). After the TAP has finished creating a viable activity plan, it is critiqued at an Activity Plan Approval Meeting attended by the SOWG Chair, instrument sequencers, rover mobility planner, uplink verification lead, and tactical uplink and downlink leads. A time-ordered listing from MAPGEN is used as the input for the sequencing process. Finally, the approved and validated sequence is radiated to the rovers to command the next Sol's activities.

The overall time for the every-Sol tactical process is tight and MAPGEN use is required to be completed within a very narrow window. Figure 1 shows the allotted period for Constraint Editor and MAPGEN use within the tactical process. (The Constraint Editor is used in the "Activity Refinement" box, while MAPGEN is used during the "Activity Plan Integration & Validation" phase.)

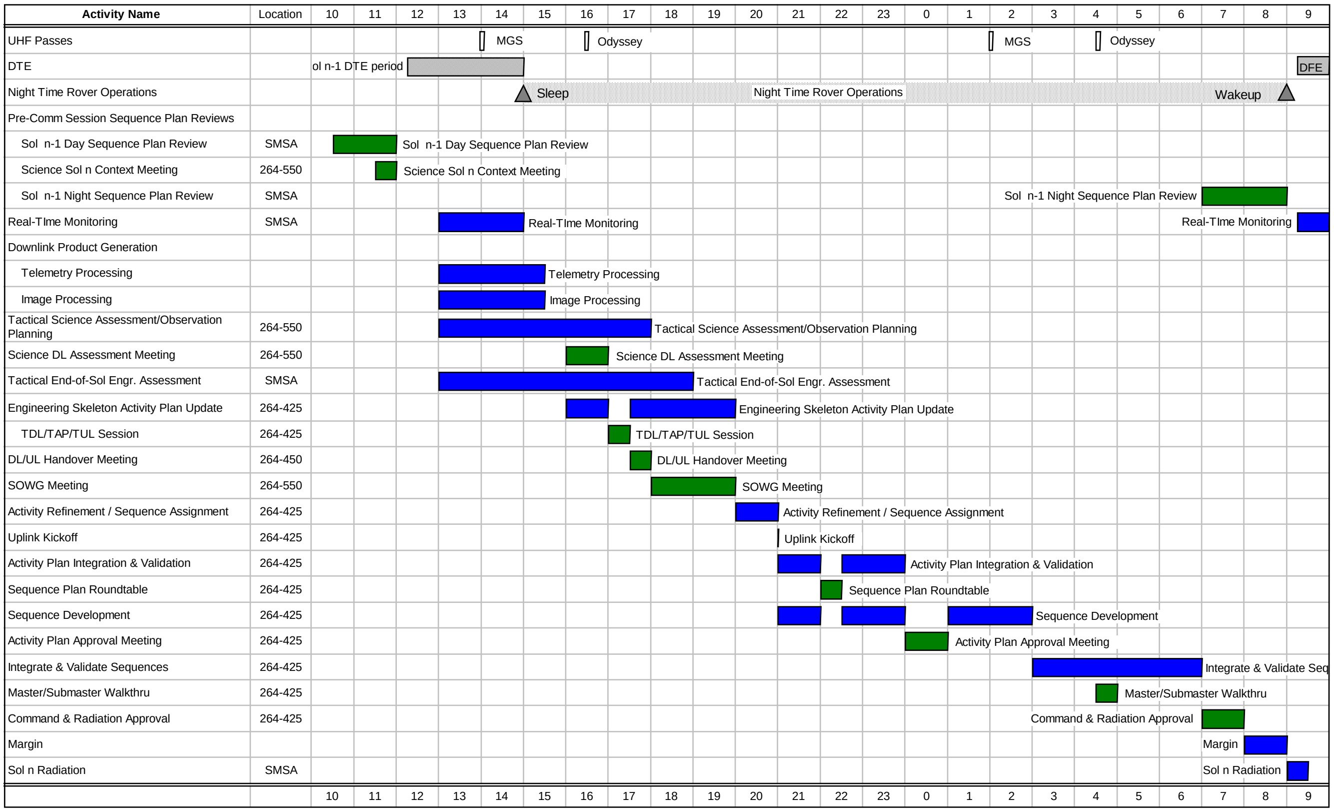

Figure 1. MER uplink process

MAPGEN provides interfaces to and from a number of other tools that are used in the uplink process. The decisions at the SOWG meeting are recorded using an activity editor tool called the Science Activity Planner (SAP) and output from this is used to populate the observations in the Constraint Editor described above. At the other end, the time-ordered listings from MAPGEN are used as input to the sequence building process, which culminates in a command sequence being radiated to the rovers. Figure 2 shows the flow of information between these different systems.

Figure 2. Use of MAPGEN within the MER Uplink process

Multi-Mission Tool

MAPGEN is integrated with APGEN, which is a well-established multi-mission tool of JPL's Telecommunications and Mission Operations Directorate (TMOD). It presents the same graphic user interface as APGEN, but with additional menu items that provide an entry to the advanced planning and constraint-reasoning capabilities.

The code base of MAPGEN provides a general planning capability that is not limited to MER. As with APGEN, the mission-specific information is captured by separate high-level adaptation/model modules that are customized for the mission. These modules describe the environment in which the vehicle operates, the constraints in the use of its instruments, and in their operation; in other words the *physics* of the operating environment in which the vehicle is situated. These models are described in a rich representation, which is human readable.

MAPGEN, therefore, is a reusable multi-mission tool that will be applicable to future missions for ground operations. In future applications (not limited to rover missions), it can be expected to play a role similar to that in MER, but with an expanded scope. In particular, now that the tool has proven itself, its use can be expected to grow in several ways:

1. Other phases of activity planning can be consolidated with the MAPGEN phase, thus making increased use of the capabilities offered in MAPGEN and increasing the benefit obtained from the automated reasoning and active rule checking it provides.
2. Additional flight rules and constraints can be encoded in the adaptation of the MAPGEN tool, thus relieving users and engineers of having to check and verify those rules.
3. Currently, MAPGEN outputs only a traditional time-ordered listing. The Mars Exploration Rovers are commanded using event-driven sequences, not traditional time-tagged sequences. In cases where the intent is not to start an activity earlier than a certain time even if the rover finds itself running ahead of schedule, WAIT_UNTIL commands are inserted by the human sequencers, based on a verbal briefing by the Tactical Activity Planner. Since MAPGEN contains all the constraint knowledge necessary, it could automatically generate WAIT_UNTIL commands.
4. There is no reason, in principle, that the activity plan produced by MAPGEN cannot be expanded directly into commands to be sent to the rover, subject to editing by humans when necessary.

c. Provide details describing how the contribution works or operates relative to system, subsystem, components, etc.

<u>MAPGEN system details</u>

MAPGEN is a mixed-initiative reasoning system. This means that the use of MAPGEN is not used within a batch process, where the user pushes a button and the software produces a final product. Instead, a MAPGEN session involves an interactive collaboration between the human user and the autonomous reasoning component in which decisions are shared and information flows in both directions from the software to the human user and vice-versa.

The MAPGEN system consists of four major components, two of which are established and proven systems:

- APGEN, a mission operations tool developed at JPL, provides the front end and visual interface for plan examination, plan editing, as well as resource checking and display.
- EUROPA is a constraint-based planning framework that provides the core automated reasoning capabilities, both in terms of active constraint enforcement and planning.
- Constraint Editor is a new tool that provides a visual interface for adding and editing plan constraints. This has been developed specifically for use with MAPGEN,
- The MAPGEN connecting component provides the interface between APGEN and EUROPA, as well as packaging various autonomous reasoning capabilities into a set of tools for the users.

See Figure 2 above.

APGEN is an established mission activity planning tool, developed at the Jet Propulsion Laboratory. It is an interactive plan editing system that allows users to view and edit plans via a graphical interface. Within MAPGEN, the APGEN component provides the plan visualization and plan editing interface, along with resource modeling and visualization.

The EUROPA system is a constraint-based planning framework that has been developed at NASA Ames Research Center. The system offers a powerful plan representation and reasoning capability, sufficient to express and reason about the complexities of real world applications, including NASA spacecraft operations. This was crystallized in the Remote Agent Experiment in May 1999, in which the Remote Agent operated the Deep Space One spacecraft autonomously for several days. EUROPA is an evolution of the planning capabilities of the Remote Agent.

The EUROPA planning framework is built on the notion of expressing information in terms of variables and constraints on those variables. This allows the system to reason effectively about partial plans, something that is essential in mixed-initiative applications like MAPGEN. In addition, the constraint-reasoning component enables MAPGEN to provide a number of useful tools and services to the user, particularly continuous automatic flight rule enforcement. The EUROPA functionality, as used in MAPGEN, can be viewed in part as providing an active database, where changes to the database result in other changes being automatically propagated. The consequent changes are logical conclusions drawn by the automated reasoning system, based on the current database and the rules that have been specified for the domain in question in the Planner model. For MER, the domain rules describe the rover activity types, their characteristics, and the flight rules that apply to them.

The APGEN-EUROPA connection component provides the glue that ties the two systems together and presents the autonomous reasoning capabilities in a packaged form suitable for use in MAPGEN. This interface provides the mixed-initiative capabilities of the system. The functionality of the interface can be divided into two categories:

1. The mapping of information between APGEN and EUROPA. Each system has its own activity plan database and the interface handles the event driven synchronization of the two data bases. When the user modifies the plan via the visual interface, the EUROPA database is automatically updated to reflect the changes. That in turn activates the automated logical reasoning component that updates the plan database according to applicable domain rules. The user can also request that various autonomous reasoning tools be brought to bear, and those in turn can also use autonomy techniques to modify the EUROPA plan. Regardless of origin, any changes to the EUROPA activity plan database are then mapped back to the APGEN plan, which in turn is reflected in the visual display for the user.

2. The packaging of useful tools for the user to apply autonomous reasoning capabilities to help build an activity plan. These tools are made available to the user via a menu in the MAPGEN interface, as well as through enhanced versions of APGEN functionality. Among these capabilities are:
    - Automatic completion of the activity plan, using automated search techniques
    - User-selected partial completion of activity plan components
    - Unplanning of activities
    - User-guided placement of activities with automatic enforcement of domain rules
    - Automatic addition of support activities, based on flight rules
    - Constrained moves, allowing the user to move activities within constraint limits
    - Reordering moves that permit the user to easily reorder activities in the plan while abiding by constraints and rules
    - Easy addition/removal of certain types of constraints to fix placement of activities

One of the key challenges that had to be addressed in the connecting component is how to map a flexible constraint-based plan into a single plan instantiation where all activities have a specific time and duration, in order to be displayed in the Graphical User Interface (GUI). Initially, the problem was solved by always showing each activity at its earliest permitted time, but this often did not reflect the user's preferences. To address this problem, a new approach had to be developed for mapping from a constraint-based plan to an instance suitable for user display. This new mapping is not only more intuitive but it allows the user to interact with the mapping, essentially giving the user a plan where the activities are displayed at, or as close as possible to, the time desired by the user.

The constraint editor is the final component of the MAPGEN system. The scientists use plan constraints to specify the coordination of activities in observations. These constraints are a crucial element of the activity planning process and are not expressible in terms of general flight rules, as they only apply to specific activity instances. The basic MAPGEN system is able to represent and reason about these constraints, but has no mechanism for adding or editing them. This is because the legacy APGEN graphic user interface was designed without reference to constraints of this kind, which are an important part of the interactive planning process. This led to the development of an external helper tool that allows the user to build and modify sets of constraints. The input to the constraint editor is a plan file from MAPGEN. The constraint editor displays the activities in the plan, along with the constraints already present, and enables the user to modify and delete existing constraints, as well as add new ones. Once the constraints have been modified, the constraint editor lets the user write out a constraint file that is then read into the MAPGEN tool. See Figure 3.

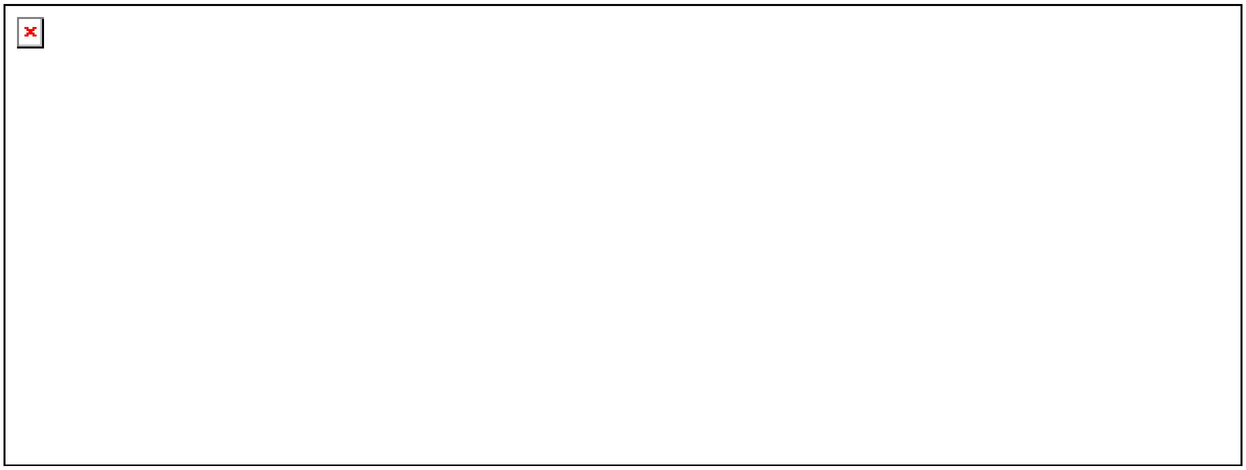

Figure 3. Round trip data flow between the Constraint Editor and MAPGEN

Use of MAPGEN within MER uplink process

MAPGEN is a general purpose activity plan construction tool, but its use in the Mars Exploration Rover operations process is both a major milestone for this software, and offers clear and concrete examples of how the MAPGEN system can be utilized.

Each sol, the scientists work to generate a set of requests for the upcoming Martian sol. At the same time, the tactical activity planner (TAP) develops the skeleton engineering activity plan (using MAPGEN) to specify the communication opportunities, the current state of the rover, and the engineering activities that should occur during the upcoming sol. Both of these are done before the activity plan integration and validation phase, which is where MAPGEN is primarily used. The first step in the activity plan integration is the specification of science constraints, for which the constraint editor is used. Since these constraints serve to codify the intent of the science requests, the MAPGEN constraint editor is one of the first successful tools for formalizing science activity intent information. Once the science constraints are in place, the main activity plan integration phase starts. During this phase, the TAP uses the constraint editor, the mixed-initiative and automated reasoning capabilities of MAPGEN via user interface, to build a complete valid activity plan for the next sol that achieves as much of the scientists' desires as possible, while abiding by all applicable flight rules and staying within resource limitations. Once this process is completed, the activity plan is approved in a meeting and then passed on to the sequence generation process. See Figure 2 for the system level block diagram of the Activity Planning tools and processes.

2. SIGNIFICANCE.

a. *Explain why the contribution is significant: scientifically, technologically, or from a humanitarian viewpoint, to the aeronautics, space community, and non-aerospace commercial activities.*

MAPGEN and its use in the MER mission is a breakthrough in development and application of more intelligent and capable ground support tools for NASA missions. It has demonstrated that computing techniques can be combined with human knowledge and insight in a way that greatly benefits mission operations. Furthermore, it has had a significant impact on the science return from the Mars Exploration Rover mission.

Computer Science

From a computer science and technological development perspective, MAPGEN is one of a very small set of advanced AI tools that offer mixed-initiative interactive plan development to users. In a mixed-initiative system, the human user is in control, guiding and monitoring the progress of automated reasoning methods, and can override them if necessary. This provides the advantage of automating routine reasoning tasks while continuing to benefit from human insight. Mixed-initiative systems aim to seamlessly integrate AI-based technology and human decision-making: something that is of great importance, but has proven to be difficult to achieve. Consequently, the successful integration of such planning tools into real-world operations is rare, making the success of MAPGEN a major achievement.

In addition, MAPGEN includes a number of notable advances in the field of mixed-initiative planning, in particular:

- Interactive constrained edits (constrained moves) – this technique allows users to modify the plans within the limits of the constraints and immediately see the overall impact of the changes made.
- Preferred temporal solution display for flexible plans – this brand new method for selecting single instantiations of flexible plans has proved to provide a very natural representation of the plan to the users, which has long been a difficult challenge
- Constraint-based mixed initiative planning with complex domain rules – the majority of previous mixed-initiative systems use simpler planning paradigms. MAPGEN is fully equipped with advanced flexible, quantitative constraint-based planning capabilities.

In more general terms, MAPGEN is a ground-breaking mixed-initiative tool that makes advanced artificial intelligence reasoning techniques, such as automated planning, plan repair and constraint reasoning, accessible and useful to users with no training in artificial intelligence.

Operations Support Technology

In terms of spacecraft operations technology, MAPGEN is a major leap forward in improving the capabilities of the tools used to operate spacecraft and other complex assets in space. Up to this point, most tools that have offered automation support for mission operations have done so only in terms of pre-defined algorithmic methods, such as scripts and macros. MAPGEN, on the other hand, automatically adapts the automation to the situation at hand. A prior tool called Plan-It-II, a forerunner of APGEN, allowed customized planning and scheduling support algorithms to be written in Lisp as part of the adaptation. This approach, with its burden of writing additional code, stands in contrast to MAPGEN, which uses a more easily adapted declarative model. In addition, the mixed-initiative nature of MAPGEN integrates the automated reasoning and planning capabilities seamlessly into the system's user interface.

The key advance of MAPGEN is that it enables operations staff to focus on the essential decisions that require human insight to make. This is due to the conflict resolution, constraint satisfaction, flight rule enforcement, among other things, being done automatically while the human user is modifying the plan. Furthermore, the automation in MAPGEN is built on flexible computational techniques that can reason from first principles about each situation, and thus easily adapts to new and unforeseen situations. This significantly reduces the brittleness that commonly has plagued automated operations support tools.

NASA Missions

Finally, as far as space exploration and NASA missions, the tool offers a new level of efficiency and safety in the activity planning process for future missions. Automatic plan generation and active constraint enforcement make it possible to explore many more options than ever before, thus yielding better plans that achieve more science in a more efficient manner. The active flight rule enforcement also increases safety by relieving the operator of having to check flight rules for complete plans. This is not only an issue of operator workload, but of reliability as well; when flight rule violations must be fixed manually, it is very difficult to ensure that the changes do not introduce other violations.

b. Estimate the degree of scientific or technological significance by a mark on the line below:

0___________1_______________2___________________3_________________4_______X_________5

None ***Modest*** ***Average*** ***Major*** ***Maximum***

c. Estimate the significance of the contribution relative to a specific NASA program or mission by marking the line below:

0___________1_______________2___________________3________ ________4________X ________5

None ***Modest*** ***Average*** ***Major*** ***Critical***

3. STAGE OF DEVELOPMENT.

Indicate the stage of development of the contribution by a mark on the line below:

0___________1_______________2___________________3_________________4_______X_________5

Concept ***Simulated*** ***Tested*** ***Fully Developed*** ***Operational***

4. ASSESSMENT OF USE.

a. If the contribution is now in operation, describe its performance and value within both the aerospace field and its application to non-aerospace commercial and government uses.

The MAPGEN software package (including the Constraint Editor tool and MAPGEN) has been in use on the MER mission since the beginning of nominal surface operations for both rovers, as part of the daily uplink process. Each Sol, a human operator uses the system to transform a prioritized "wish-list" of observations into a schedule of activities for the Sol that satisfies the scientific intent and fits within the rover's resources. This is then used by the sequencing team to construct detailed sequences of commands that are radiated to the rover on Mars.

Prior to the availability of MAPGEN (for example on the Mars Pathfinder mission), the creation of an activity plan was performed in a more manual and ad-hoc fashion, using more conventional tools such as electronic spreadsheets. Instead of being formalized, constraints were expressed in English, and the burden of interpreting and enforcing them fell on the shoulders of the human planner. Once a plan was formulated, there was a high price to pay for any subsequent modification, since all the constraints would have to be rechecked and reestablished. In order to make the complex planning task more manageable, various simplifications were introduced such as creating rigid "science windows" in advance. However, this impaired the flexibility of the plan and reduced the amount that could be accomplished. Because of the burden on human planners, the process was more error-prone. Indeed, based on the Mars Pathfinder experience, it was expected that one out of every three Sols on MER would be "wasted" in coping with various issues, including those arising from the commanding process.

By contrast, on MER, the activity planning process has gone more smoothly than expected. Richard Cook, the MER Project Manager, has stated:

> *One group in particular deserves special mention for this accomplishment, namely the team responsible for putting together the daily uplink products. The effort to plan and develop a new set of activities every day is clearly the most difficult aspect of surface operations, yet those of you in the "boiler rooms" have made it look easy.*

Except for the time required to recover from the Spirit flash memory anomaly (about a week), every Sol of normal surface operations has produced a substantial science return with the use of MAPGEN. This achievement has in part been based on the success of the activity planning process, which in turn is greatly enhanced by the use of MAPGEN. Once the TAPs had become familiar with the MAPGEN tool, they were typically completing the activity planning process in a fraction of the time allotted, and still fitting in most of the science request that could be fit into the plan; not only the highest and second-highest priority observations, but often a large portion of lower priority "bonus" observations as well. Indeed, the limiting factor has typically been the amount of resource available on the rovers rather than the amount of time available to the TAP to work on the plan. (Ironically, the success of the activity planning process using MAPGEN, has led the sequencers downstream to complain that the plans are so complex that it is a challenging task to sequence them!) Finally, the use of MAPGEN has made the TAPs so confident about the planning process that they are willing to consider substantial changes to the plan late in the planning process allowing late-breaking information to be incorporated in the next sol's plan.

To summarize, the MAPGEN software package has successfully been used as an integral part of mission-critical operations, thus opening the door to more extensive use in the future. Since the software is general, and can be customized to specific applications via a separate adaptation module, its application can certainly be extended beyond the aerospace domain to other tactical planning needs, such as those outlined in section 7b below.

b. If the contribution is not now in operational use, describe its most likely or previous applications and the extent of commercial,(includes non-aerospace commercialization) government and/or NASA-specific uses.

It is currently in operational use.

c. Will the contribution increase in value or in its applications over time and in what manner?

The core technology is general and thus applicable to future missions. As missions become more complex and extended, the value of using this technology will increase significantly.

5. CREATIVITY.

What is your assessment of the creativity displayed in the conduct of this contribution, relative to the expected performance of those in similar positions?

*None________Low __________Modest_________Average________High_________Very High*_____X_____

6. RECOGNITION

What forms of recognition have been received by the contributors for this contribution? Have previous awards been made to the contributor(s) for this accomplishment? Please describe.

The MAPGEN team was recognized by NASA Ames for the First Information Sciences Infusion award in 2002 and the MER team infusion team award in 2003. NASA Tech Brief evaluated MAPGEN and made a cash award to all the authors of MAPGEN. Ames and JPL center management have recognized their employees and contractors on this effort and bestowed various awards. The team was invited to write a paper for the well-read IEEE Intelligent Systems magazine track of ‘AI in Space’. The PI and the software was also featured in the front pages of regional newspapers like the Ft. Worth Star Telegram, Ft. Worth Business Press and for National Engineering Week in the Dallas Morning News. Other media coverage include, the national English language daily’s of India, including the Times of India, Hindustan Times, Financial Express, Economic Times and Deccan Chronicle in addition to specialty magazines SiliconIndia and India Abroad. Members of the team have been asked to present tutorials in the Ground Systems Architectures Workshop, Manhattan Beach, California, an invited talk at the Ninth Congress of the Italian Artificial Intelligence Society, Perugia, Italy and the keynote address at NASA’s Intelligent Systems Workshop at Dana Point, California all in 2004.

7. TANGIBLE VALUE.

As a measure of the tangible value of this contribution, estimate the following:

a. NASA cost savings to date and in future years.*

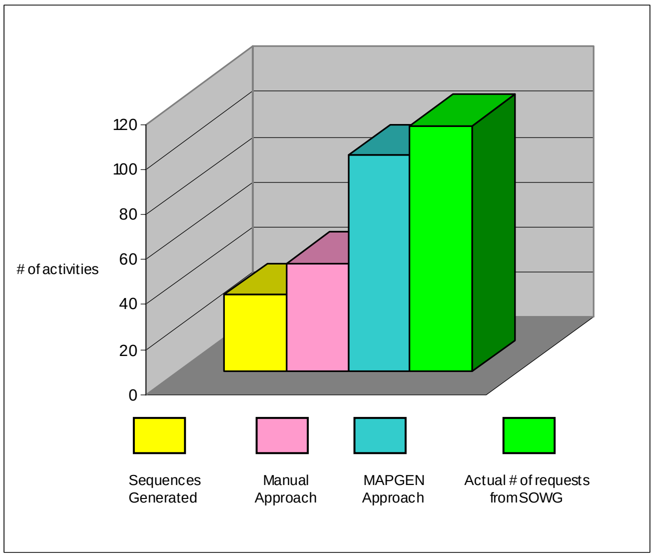

Figure 4. Experimental comparison of science return from using MAPGEN versus manual methods.

The most tangible benefit of MAPGEN use to date has been in terms of increased science return during the MER mission operations, rather than a reduction in total cost. Figure 4 shows the result of an experiment carried out during the Operational Readiness Tests that compares the number of activities planned using MAPGEN versus a manual approach for the activity plan generation process.

An increased science return may be viewed as a reduction in cost per item of information returned. Mission personnel have estimated the increase in science return during operations as being between 20 and 40 percent. To put a dollar figure on the value, based on the above estimate, with the total mission cost being over 800 million dollars, the value added by the tool can be calculated as ranging from $160 million to $320 million for an investment of $4.25 million in full-cost dollars for the nominal mission of 90 Sols.

In future uses of MAPGEN, the returns are likely to be a combination of improved efficiency and savings in total cost. Savings in total cost should arise from fewer operations support staff, since the tool significantly reduces the time and effort required to develop a good activity plan. As the system continues to evolve and grow with future missions, these improvements are likely to increase over time with a small investment in the infrastructure.

b. Current market value and potential as a commercial product or process.

The tool has not been evaluated for commercialization, but it does offer capabilities that are relevant in at least the following kinds of operations:

1. Operating complex systems in dynamic environments, where safety is critical, either due to cost or danger. One obvious example is that of commercial satellites, which are complex and expensive assets that have to be

carefully operated. Another example is that of certain production facilities such as chemical refineries, where operations change from day to day, based on production needs, and safety is a critical issue.

2. Planning and re-planning complex operations where minimizing cost and maximizing efficiency has to be done in response to unforeseen changes and events. Such is the case, for example, for complex construction activities, such as large structures and aircraft, where efficiency and minimal downtime is crucial, but constraints and dependencies are too numerous and complex for humans to easily keep in mind.

Since MAPGEN is a general purpose system, it can be adapted to handle activity planning for many kinds of operations, including those outlined above. Many of the same issues arise in commercial applications as in spacecraft operations, namely that human operators may still want to make specific decisions, but can greatly benefit from assistance with constraint enforcement, plan completion and other such tasks. Consequently, the expectation is that MAPGEN and the underlying technology have great potential for infusion into commercial operations.

c. *Other measurable value: increased efficiency, enabling technology, improved management, etc.*

The demonstrated value of the MAPGEN tool is in improving the activity planning process, resulting in safer plans with increased science return being generated in less time and with less effort.

- Improved science return: MAPGEN can automatically generate plans of size and complexity that users find daunting to understand, much less build by hand. This means that more activities can be placed in the plan, thus increasing the amount of science data gathered. MAPGEN can also assist the user in modifying a given plan, to fit in even more activities, further increasing the science return.
- Safer plans: MAPGEN automatically enforces certain flight rules while the user works with the plan, thus freeing the user from having to keep track of the rules and potential violations. A key benefit of this capability, in addition to improving the user's ability to generate plans, is that flight rule violations are much less likely to slip in by accident. Consequently, the resulting plans are safer, especially when tight deadlines limit the amount of double and triple checking the user can reasonably do.
- Decreased time and effort: The difference between the time it takes to build a complete valid plan by hand, and the time it takes the automated planning capability to generate a valid baseline plan can be an order of magnitude. In addition, the active flight rule and constraint enforcement allows the user to quickly make changes that involve a large number of activities and would thus be time-consuming or impossible in manual operations

APPLICANT'S SIGNATURE: ______________________________________DATE:____________

SECTION II COMMENTS AND CONCURRENCE

1. EVALUATOR

I recommend/do not recommend a Space Act Award for this contribution for the following reasons.

Printed Name and Signature	*Title*	*Date*
NASA Installation	*Contractor*	*Other*

2. EVALUATOR'S SUPERVISOR

I support/do not support a Space Act Award for this contribution for the following reasons.

Printed Name and Signature	*Title*	*Date*

3. TECHNICAL MANAGEMENT (required signature)

I support/do not support a Space Act Award for this contribution for the following reasons. Further, I verify that the contribution is significant to NASA Aeronautics and space Activities and that NASA has adopted, supported, sponsored or used this scientific or technical contribution.

Printed Name and Signature	*Title*	*Date*

4. TECHNOLOGY TRANSFER MANAGEMENT

I support/do not support a Space Act Award for this contribution for the following reasons.

Printed Name and Signature	*Title*	*Date*

TO BE COMPLETED BY AWARDS LIAISON OFFICE

5. IDENTIFICATION OF CONTRIBUTORS

Contributor Name	***Employer***	***Percentage of Contribution***
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Ari Jonsson	RIACS/NASA Ames	12
John Bresina	NASA Ames	12
Bob Kanefsky	QSS Inc/NASA Ames	12

Kanna Rajan	NASA Ames	12
Mitchell Ai-Chang	QSS Inc/NASA Ames	5
Jennifer Hsu	Foothill DeAnza College	5
Jeffrey Yglesias	QSS Inc/NASA Ames	5
Leonard Charest	JPL	4
Kimberly Farrell	QSS Inc/NASA Ames	3
Conor McGann	QSS Inc/NASA Ames	2
Adam Chase	JPL	2
Will Edgington	QSS Inc/NASA Ames	2
Pierre Maldague	JPL	2
Nicola Muscettola	NASA Ames	2
Michael McCurdy	NASA Ames	1.5
Brian Chafin	JPL	1.5
Alonso Vera	NASA Ames	1
Adans Ko	JPL	0.5
Aaron Staley		0.5
Richard Springer	JPL	0.5
Ernest Mark Floyd	JPL	0.5
Jim Murphy	San Jose State/NASA Ames	0.5
Alan Baba	JPL	0.5
Irene Tollinger	NASA Ames	0.5
Curt Eggemeyer	JPL	0.5

NASA Case Number__________

6. PATENT INFORMATION

Patent Applied for? Y/N Granted? Y/N	*Serial Number or Patent Number*
Application filed by: Government? Non-Government?	*Date Filed or Granted*
License Granted Y/N	*Company Name:*

7. EVALUATION NUMBER 1 2 3

8. BUSINESS ADDRESS OF CONTRIBUTORS IF OTHER THAN NASA EMPLOYEES

9. AWARD LIAISON OFFICER COMMENTS AND SIGNATURE (required)

Printed Name and Signature	*Comments*	*Date*